1968

The satellites of Mars

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THE SATELLITES OF MARS

by

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APPROVAL SHEET

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Master of Science, 1968

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ABSTRACT

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Thesis directed by: Assistant Professor Michael F. A'Hearn

The two satellites of Mars, Phobos and Deimos, are investigated in depth from the time of their speculative prediction by Swift in 1726 and their discovery by Hall in 1877 up until the latest observations during the 1967 opposition. A reasonable explanation for Swift's prediction is set forth.

The proposal by Sharpless in 1945 that suggested a secular acceleration in the longitude of Phobos stirred considerable controversy over its possible causes. All proposed causes are investigated here and all but tidal effects are discounted.

Wilkins has recently analyzed the available data by computer with the object of arriving at improved orbital elements. He discovered no support for a secular acceleration in longitude.

Unsuccessful attempts by the author to observe the satellites photographically during the 1967 opposition are described with particular attention given to the peculiar problems of photographing faint sources in close proximity to very bright ones.

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Norman A. Ross

Thesis submitted to the Faculty of the Graduate School
of the University of Maryland in partial fulfillment
of the requirements for the degree of
Master of Science
1968

ACKNOWLEDGEMENT

The author wishes to express his thanks to Professor Michael A'Hearn, who directed work on this thesis, for his helpful assistance and patience during its preparation.

The author is indebted to Mr. J. R. Fisher for his valuable assistance with many phases of the observational work.

Funds for the author's course of study and for related expenses have been provided under a grant from the Office of Naval Research for the Advanced Science Program for active-duty naval officers which is administered by the U. S. Naval Postgraduate School, Monterey, California.

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INTRODUCTION

Since their discovery in 1877 the two moons of Mars have received scant attention. In 1945 Sharpless' proposal that the inner satellite, Phobos, shows secular acceleration caused renewed interest and controversy. More recently the Mariner IV probe of Mars and the imminence of manned exploration, perhaps in this century, have stirred interest in this subject.

Aside from gaining knowledge of the satellites for its own sake, studying them yields other valuable benefits. In the first year after their discovery Hall was able to calculate the mass of Mars to an accuracy previously unattainable. His value of $1/m = 3,093,500 \pm 5000$ in reciprocal solar masses compares well with the value determined by tracking the Mariner IV probe, $3,098,600 \pm 600$, which is probably the most accurate value available today. Struve as early as 1895 used data on the motions of Phobos to derive values of flattening and the gravitational harmonic constant J_2 for Mars. His values were $1/f = 192$ (150 ± 50) and $J_2 = 0.00192$ (0.00196 ± 0.0005) where the presently accepted values are in parentheses.

If the inner satellite does exhibit a secular acceleration, then we may draw inferences regarding the composition of Mars from supposed tidal effects. Or perhaps we could derive values of density of the exosphere if drag effects are responsible for the acceleration. The weaknesses of these two propositions will be discussed in detail in Chapter III.

Rakos (1965) used a new photoelectric scanning technique during the 1965 opposition to observe eclipses of Phobos by Mars as a means of estimating the atmospheric pressure on the surface of the planet. The equipment consisted of a photomultiplier able to respond to very rapid changes in intensity and a very narrow slit, adjustable between 50 and 500 microns. Using an arrangement of mirrors and drives, the photomultiplier scanned the length of the slit at a pre-set rate of either 2.5, 5, or 10 scans per second while the slit was swept across the selected area of the sky. An oscilloscope continuously photographed the output of the photomultiplier. In this case it was necessary to integrate over a large number of frames to get the decrease in brightness of Phobos as it disappeared behind Mars. On a typical night 36,000 scans were made over a period of one hour during which the eclipse lasted for about 15 minutes. On the basis of his observations with both the 61-inch astrometric reflector of the U. S. Naval Observatory at Flagstaff, Arizona, and the 84-inch telescope at the Kitt Peak National Observatory, Rakos (1967) obtained an upper limit of 30 mb on the surface pressure on Mars. In addition he concluded that the absorption level causing the blue haze is not higher than 10 km above the surface.

Werner von Braun has said that the first space travelers to Mars will either orbit the planet or preferably land on one of the natural satellites to make their observations. The primary advantage to landing on Phobos (or Deimos, perhaps) over landing on the surface of Mars itself is in propellant savings. An energy saving corresponding to a velocity increment on about 3.4 km/sec is realized over braking to a stop on the Martian surface. Not only does this avoid the problems of entering the Martian atmosphere, but many of the lunar landing techniques could be applied. After initially using the station on Phobos to observe the surface of Mars preliminary to establishing a base camp on the planet's, surface, there are decided advantages to maintaining the satellite station for resupply, storage, and later on even as a source of fuel. A vehicle to haul supplies from the satellite to the planet's surface and shuttle back again would require only about 13 tons of propellant for the return flight to Phobos. This figure assumes that aerodynamic braking is used on the entry into the Martian atmosphere and that the empty container weighs 5 tons. Steinhoff (1966) even discusses the possibility of mining and processing the minerals of the satellite itself into propellant and life-support materials, thus making the community on Mars more nearly self-sustaining.

CHAPTER I

HISTORICAL BACKGROUND

Were the story of the satellites of Mars to be told from the beginning, we should start in the early 1700's, a century and a half before their discovery. Jonathan Swift, an English satirist, began in 1721 on his most lasting work, Gulliver's Travels, which was to be published five years later. This is surely an unlikely source work for the first data on the objects of our research. But in Gulliver's fictional travels to Laputa he describes the work of certain astronomers there who, with the use of their optically superior telescopes, had discovered two satellites revolving about Mars.

> . . . Although their largest telescopes do not exceed three feet, they magnify much more than those of a hundred yards among us, and at the same time show the stars with greater clearness. This advantage has enabled them to extend their discoveries much farther than our astronomers in Europe; for they have made a catalog of ten thousand fixed stars, whereas the largest of ours do not contain above one third part of that number. They have likewise discovered two lesser stars, or satellites, which revolve about Mars, whereof the innermost is distant from the center of the primary planet exactly three of his diameters, and the outermost five; the former revolves in the space of ten hours, and the latter in twenty-one and a half; so that the squares of their periodical times are very near in the same proportion with the cubes of their distance from the center of Mars, which evidently shows them to be governed by the same law of gravitation that influences the other heavenly bodies.

Even more difficult to explain than their mere mention is the uncanny accuracy of descriptive detail that is given, especially when one realizes that the motions of Phobos are unique in our solar system.

Such a remarkable prophesy calls for a deeper understanding of its source. What influenced Swift to comment on the state of science in his day in these strange but perceptive terms? He was no scientist himself, nor did he have a close relationship with them, but we know that he was well read in astronomy and mathematics. His use of Kepler's laws, published in 1609, is evident in his proper matching of orbital distances and periods.

With the following description of the Laputan astronomers' work area we are given a clue as to where Swift may have learned something of the state of astronomy in Europe.

> At the center of the island there is a chasm about fifty yards in diameter, from whence the astronomers descend into a large dome, which is therefore called Flandona Gagnole, or the Astronomer' Cave, situated at the depth of a hundred yards beneath the upper surface of the adamant. In this cave are twenty lanps continually burning, which from the reflection of the adamant cast a strong light into every part. The place is stored with great variety of sextants, quadrants, telescopes, astrolabes, and other astronomical instruments.

Brinton (1956) sees this cave as based on a visit by Swift to the Royal Observatory in Paris where there were caves for laboratory experiments.

Although Richardson and Bonestell (1964) and Malcolm (1957) attribute Swift's predictions to mere chance, there is a tenable explanation. It was reasonable at that time to guess that Mars may have had two moons since the Earth has one and Jupiter was thought to have four and Saturn at least five. Kepler had made that suggestion in a critique of Galileo's Sidereal Messenger in 1610.

Why then did Swift choose the distances as accurately as he did? Table I compares Swift's with the actual values of distance and period for both satellites as determined by Hall (1878) upon their discovery.

Satellite	Distance from center of Mars		Period of revolution	
	Swift	Hall	Swift	Hall
Phobos	3 diameters	1.38 diameters	10^h	$7^h\ 39^m$
Deimos	5 "	3.46 "	$21^h\ 30^m$	$30^h\ 18^m$

Table I. Comparison of Swift's predictions with actual values of the orbits of Mars' satellites.

Although these Laputan astronomers were far from perfect, we must somehow account for their coming as close as they did. Levitt (1956) has suggested that perhaps Swift in his researching for Gulliver's Travels had read in an astronomy book by David Gregory published in 1713 that Jupiter's closest satellites were at 5-2/3 and 9 semi-diameters. He used the same values for Mars, rounding up to get the distance in integral diameters. Then he applied the well established Third Law of Kepler to arrive at consistent orbital periods for the satellites.

After Swift's fictional description of the two Martian moons, reference to them was made by Voltaire in his Micromegas, which is a tale of interplanetary space travel.

Asaph Hall began his search for satellites of Mars with serious doubts of any success. Although he had the new 26-inch Clark refractor of the U. S. Naval Observatory at his disposal, there had been many previous unsuccessful attempts. The most recent had been a rather cursory search by D'Arrest in 1862. Of some encouragement was the fact that no thorough search had been made for nearly a hundred years, since that of Sir William Herschel in 1783.

At first Hall investigated several faint objects at some distance from Mars which proved to be stars. Then on August 10, 1877, he began checking the region close in to the disk, in the glare of the planet. His technique was to position Mars just outside the field of view of the eyepiece as he searched all the way around the disk. The following night (at 0230 on August 12) using the same procedure he came upon a faint object which later turned out to be Deimos, the outer satellite. However, unfortunately fog from the Potomac River prevented a further verification. Weather prevented any more observations until the night of August 16 when Deimos was again seen. On August 17 he discovered Phobos while he waited and watched for Deimos. On that night and the following one, Professor Hall, with the assistance of a technician at the Observatory, George Anderson, who observed and confirmed their positions, obtained positive verification of the nature of the objects as satellites. On August 18 Admiral Rodgers, Superintendent of the Observatory, announced the discovery, which was subsequently given wide public hearing. In 1878 Professor Hall was awarded the Gold Medal of the Royal Astronomical Society for his work (Lindsay, 1879).

There was no challenge from within the scientific community of the authenticity of Hall's discovery. In fact, according to Hill (1908) no other astronomer was even attempting a similar search in 1877. After the announcement several smaller telescopes were used successfully to observe the satellites. Hall continued in a program of observations until October 31. It was not long before he was able to determine that the inner satellite was the brighter because he was able to observe it until it approached to within 8 seconds of arc of the limb, while the outer one was visible only beyond about 25 seconds from the limb. He chose the names of the moons at the suggestion of a Mr. Madan of Eton, England, from the Iliad which gave the sons (or attendants) of the god Mars as Deimos (panic) and Phobos (fear).

Hall recorded his observations in polar coordinates, giving the position angle and distance from the center of gravity of the apparent disk of the planet. His method of measurement was as follows. The disk of the planet was bisected by eye with one wire of the micrometer while the other wire was placed over the satellite. Since both Mars and the satellite being observed were not simultaneously in the field of view, the eyepiece had to be slipped back and forth until both wires appeared to be accurately placed. Hall recognized that a double wire would have enabled him more precisely to center on the disk of the planet, but he was not willing to interrupt the procedures he had already begun. In computing orbits he applied corrections for refraction and for the figure of the true disk.

CHAPTER II

BASIC DATA ON THE SATELLITES

From the time of Hall's discovery of the satellites until the present, they have been studied with the object of refining their orbital elements and of obtaining their colors and a more firmly established basis for estimating their size. Table II summarizes some of the significant facts about Phobos and Deimos. This author has chosen from occasionally contracictory estimates those which are judged to be the best supported by available data. The source of each entry is given, and there follows a brief discussion of some of the less obvious entries.

The physical characteristics of the two satellites are difficult to determine due to their small size and close proximity to Mars. Observations over the years have failed to show any short-term variation in brightness of either satellite. To Shklovskii (1959) this supported his view that they must have smooth, even surfaces as if they were man-made spheres. One would expect such small bodies, if the are natural, to be fairly irregular, as are asteroids. Tombaugh (1959), however, points out that few asteroids are known to vary in brightness, hence the non-variability of the satellites is not conclusive as to their shape. He observed more than 1500 asteroids in his search for trans-Neptunian planets, and only a "small fraction" showed any variation in brightness. The variable asteroid, Eros, is known to have a very elongated shape. It is entirely possible then that the Martian satellites have much the same shape as the average asteroid.

Tombaugh also takes issue with Shklovskii's assumed albedo of 0.15 for Phobos, the same as that of Mars. His claim is that a much lower albedo should be expected, approximately 0.07 as for the Moon and Mercury. Unlike Mars, the satellites have no atmosphere to increase their albedos.

Table II

Selected characteristics and orbital elements of Phobos and Deimos

	Source	Phobos	Deimos
Shape	Tombaugh (1959)	Irregular	Irregular
Composition	Steinhoff (1966)	Same as Martian surface	
Albedo	Tombaugh (1959)	0.07	0.07
Color	Antoniadi (1930)	White	Blueish
Size, diameter	Tombaugh (1959)	24 km	12 km
Semimajor axis*	Wilkins (1965)	12″.91 ± 0″.01	32″.36 ± 0″.01
Eccentricity of orbit	Wilkins (1965)	0.018 ± 0.001	0.0 ± 0.0003
Mean daily motion (tropical)	Wilkins (1966)	1128°.8443 ± 0°.0001	285°.16188 ± 0.00001
Inclination of orbital plane to Laplacian plane	Wilkins (1966)	0°.9 ± 0°.1	1°.80 ± 0°.02
Rate of regression of node (daily)	Wilkins (1966)	0°.438 ± 0°.001	0°.0180 ± 0.0003

* Apparent angle at 1 a.u.

Professor Hall, when he first discovered the satellites, was able to determine from his brightness estimates that the inner satellite was the larger of the two (see page 10). The currently accepted values of diameter, estimated at 16 km for Phobos and 8 km for Deimos, are based on the assumed albedo of 0.15 and the measured brightness. But if Tombaugh's lower estimate of 0.07 is more nearly correct, one should revise the diameters upward to approximately 24 and 12 km.

Antoniadi (1930) has qualitatively described Deimos as bluer than Phobos. Although the difference may have been due solely to the glare from the "red" planet, it is accepted for lack of any other descriptive data. Harris (1961) during the favorable 1956 opposition obtained a B-V for both satellites of 0.6 compared with a mean value of B-V for the planet of 1.36. Both of these results need the support of additional observations.

Their physical composition must, of course, be related to their origin, presumably either by asteroidal capture or from being thrown or blown off the Martian surface. One might conclude that since the satellites appear neutral in color and Mars, due to the large amount of limonite in its surface, is reddish, then the satellites must not have originated on the Martian surface. Shklovskii and Sagan (1966) deny, however, that an apparent difference in the chemical composition of their surfaces necessarily implies that they were not initially of the same material. The satellites, being unprotected by an atmosphere, may have been discolored by incident protons of the solar wind much as may have occurred with our Moon. It is known that when a powdered substance of almost any composition is irradiated in a vacuum by protons of energies comparable to the solar wind, it becomes darker and loses its original color.

Tidal torques on the small, irregularly shaped satellites probably would result in damping out all spin relative to Mars. Their close proximity to the parent planet, especially in the case of Phobos, enhances this effect.

Table II does not indicate any secular acceleration in longitude for either satellite. Evidence is presented in Chapter III, a detailed discussion of this problem, that seems to support the absence of secular acceleration in both satellites.

The inclinations of the orbital planes of the satellites are referred to the Laplacian plane, which differs from the equatorial plane of Mars by only $0\overset{\circ}{.}01$ in the case of Phobos, and $0\overset{\circ}{.}92$ for Deimos. The Laplacian plane is a fixed plane upon which the nodes of the satellite orbits steadily regress, and it is positioned such that the normal components of the perturbing forces (due to oblateness and Sun in this instance) are balanced. Oblateness is the dominating effect here, therefore the Laplacian plane is very nearly the same as the equatorial plane. The longitude of a satellite is measured from the equinox to the ascending node of the orbit on the celestial equator, then along the orbit to the satellite.

Although the ephemerides published in the American Ephemeris and Nautical Almanac, 1967 are based on orbital elements derived by Struve in 1911, the recent analysis by Wilkins (1965) of the Nautical Almanac Office, Royal Greenwich Observatory, has provided more accurate information and more realistic error estimates. Burton (1929) gives a complete tabulation of orbital elements available up until his time.

Perhaps discussion of the possibility of there being additional moons in orbit about Mars would be appropriate here. During the favorable oppositions of 1954, 1956, and 1958, Kuiper (1961) conducted a photographic search for fainter and more distant Martian satellites using the 82-inch reflector of the McDonald Observatory. None was found. He concluded that no additional satellites exist larger than 1.4 km in diameter.

Cutteridge (1962) has proposed that the so-called Bode's Law may be applied to satellites as well as to planets. That is, the mean distance $\underline{a}$ from the center of the parent planet to a satellite (and also the distance to the surface of the planet, corresponding to $n = 0$) follows a simple formula of the form

$$\log a = An + B, \qquad n = 0, 1, 2, 3, \ldots$$

where A and B are constants for a given planet. Such a relationship is shown to hold for Jupiter, Saturn (the rings as well as the satellites fit), and Uranus, with the condition that vacant positions sometimes occur. Figure I shows how such a relationship might predict possible orbits for satellites outside the orbit of Deimos. Note that the first new satellite might be expected at a mean distance of about 63,000 km from the center of Mars. Kuiper (1961) in his analysis shows that from the standpoint of orbital stability, one need not search beyond about 460,000 km. Therefore, there are two or possibly three vacant positions where small satellites might be observed, but in fact they have not been detected, and it is unlikely that they exist.

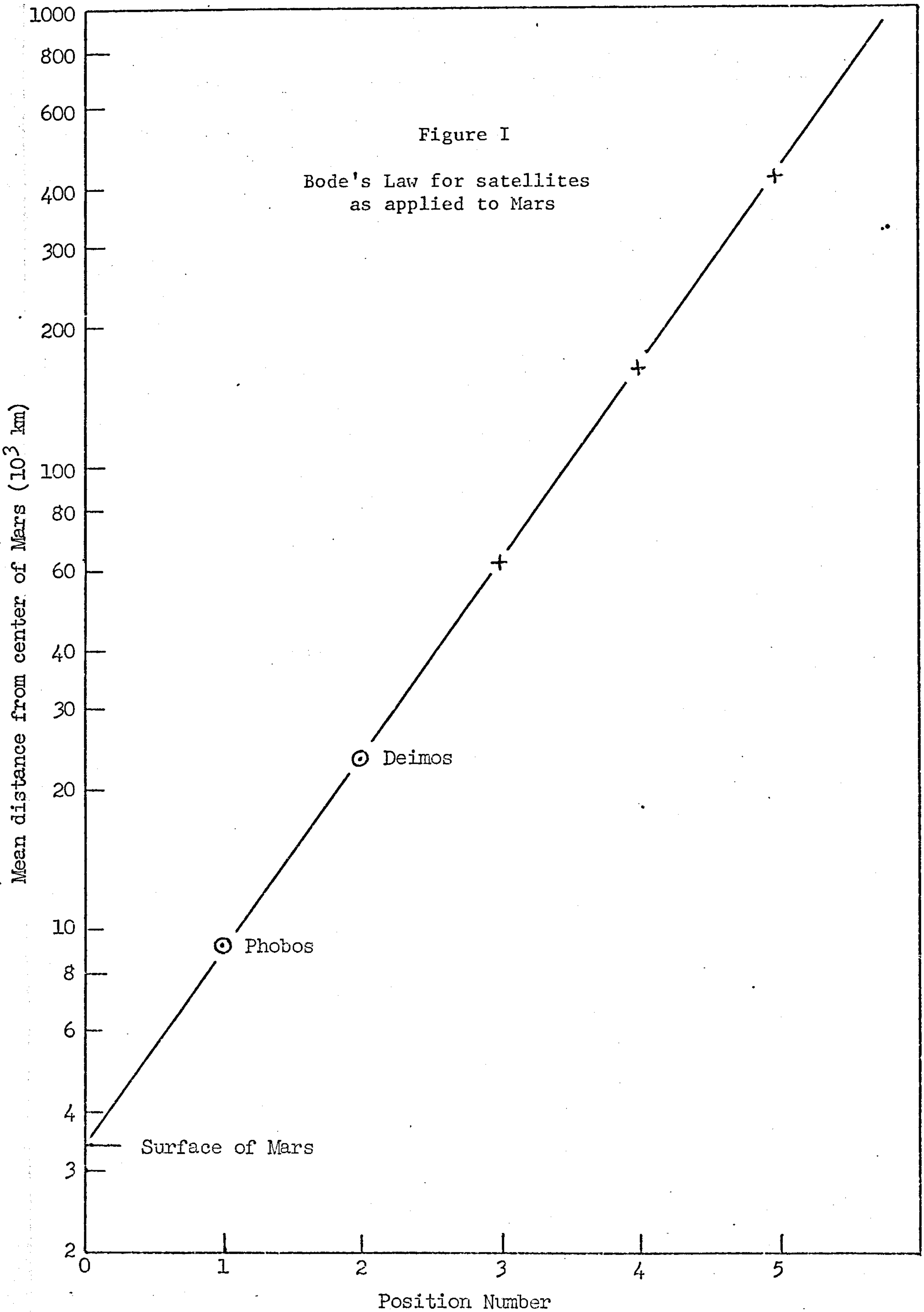

Figure I
Bode's Law for satellites
as applied to Mars
Mean distance from center of Mars (10^3 km)
1000
800
600
400
300
200
100
80
60
40
30
20
10
8
6
4
3
2
Deimos
Phobos
Surface of Mars
0
1
2
3
4
5
Position Number

CHAPTER III

SECULAR ACCELERATION OF PHOBOS

In 1945 Sharpless of the U. S. Naval Observatory declared that Phobos seems to be accelerating at a rate of about 6° advance in longitude per century. The observed acceleration of Deimos was too small to be conclusive and is ignored here. In this chapter several explanations for the acceleration of Phobos will be discussed; and finally the recent calculations by Wilkins (1965, 1966) are presented to show that there may be no acceleration after all, and consequently no basis for the controversy.

Considering the techniques used for the earliest measurements of the positions of the satellites (see page 10) and the inherent observational difficulties, considerable error may be expected. But the magnitude of the secular acceleration that Sharpless calculated suggests that it is real.

Figure II from Sharpless (1945) collects data given by Burton (1929) covering observations from 1877 to 1926, and also data from U. S. Naval Observatory observations in 1939 and 1941. Plotted are differences in observed longitude of the satellites from the mean longitude calculated on the basis of Burton's adopted values of mean daily motion ($n = 1128\overset{\circ}{.}84413$ for Phobos and $n = 285\overset{\circ}{.}16190$ for Deimos) and mean longitude for 1900 January 0.0 ($l_o = 19\overset{\circ}{.}67$ for Phobos and $l_o = 286\overset{\circ}{.}71$ for Deimos). Circles are opposition normals for a given telescope, and triangles are group means. A least squares straight line

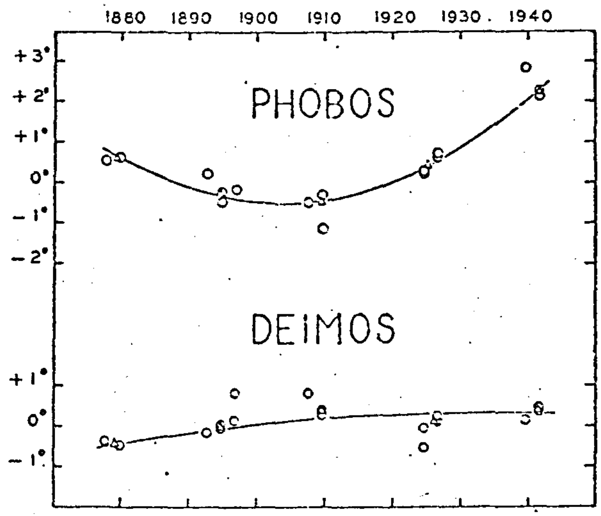

Figure II

Residuals in orbital longitude, from Sharpless (1945)

fit would imply no acceleration, and a non-zero slope would simply mean an adjustment in the value of mean daily motion is required. But the decided parabolic shape of the best fit can only mean that there is secular acceleration.

Criticism of Sharpless' proposal centered on his possible over-interpretation of the early visual observations with their inherently large probable errors, and on his 1939 and 1941 photographic observations. Normally one would expect that the photographic observations of Sharpless would be intrinsically more accurate than the visual; but the eye accommodates well to the bright disk of Mars while still being able to distinguish the faint satellites. Sharpless, rather than estimating the center of Mars, elected to settle for measuring only the relative positions of the two satellites. Though indirect, this method (used also by Roemer (1967) at the University of Arizona during the 1967 opposition) has the advantage of measuring the position of Phobos with respect to a point source, Deimos, which moves with a longer period and, if Sharpless' calculations are accurate, with little or no secular acceleration. However, this method introduces the problem of first requiring refinement of the orbital elements of Deimos, and also the problem of deciding how to split the errors between the two satellites.

Öpik (1962) draws attention to the small difference in mean daily motion between a straight line fit to the points of Figure II for Phobos and that obtained by Sharpless at either the beginning or end of his 62 year period. The difference amounts to only one part in 10^7. At the rate Phobos is supposed to be accelerating, its height above the Martian surface would be decreasing at a rate of 1.6×10^{-12} km/sec, and it would impact on Mars in about 10^8 years. From a cosmogonical standpoint, Öpik calculates that if Phobos was initially a part of the parent planet and was formed more than a billion years ago, then what we are observing is the final one percent of its lifetime, and improbable event.

But if the acceleration is admitted to be real, several possible causes should be considered.

(1) Atmospheric drag. Interaction of Phobos with Mars' exosphere would cause the orbit to shrink resulting in a net acceleration to conserve angular momentum. The resistance of the interplanetary medium in the vicinity of the satellite's orbit is a parallel consideration here.

(2) Tidal friction. Tides both on Mars and on the satellite must be investigated. Proximity to Mars and the short orbital period of

Phobos suggest that this may be an important factor.

(3) Electromagnetic braking by the magnetic field of Mars.

(4) Solar radiation pressure.

(5) Classical celestial mechanical perturbations. The effects of the Sun, of Deimos, and of Jupiter are considered.

The order given above is roughly a ranking of conceivable causes of the acceleration in descending order of probability. Items (1) and (2) have been given the most serious attention and are considered by this author as being the most worthy of consideration. Consequently, the last three items will be dealt with (dismissed?) first, and then there follows a more thorough discussion of atmospheric drag and tidal forces.

Electromagnetic braking. An upper limit on the magnetic field of Mars is known from the Mariner IV experiments to be approximately 10^{-4} gauss at the surface on the equator. An estimate of the time required for magnetic damping is greater than 5×10^{11} years, longer than the age of the solar system, and even this is based on the unlikely premise that Phobos is a good conductor. Magnetic forces are then inadequate to give any observable acceleration.

Radiation pressure. Shklovskii and Sagan (1966) estimate the force on Phobos due to the Poynting-Robertson effect, considering solar radiation and light reflected off Mars, to be some six to eight times less than is required for the observed acceleration. Shklovskii (1959) also argues that this possible cause would have more effect on Deimos than is observed.

Classical celestial mechanical perturbations. Perturbations due to bodies outside the Mars-Phobos-Deimos system, principally the Sun and Jupiter, would have a greater effect on Deimos than on Phobos. Phobos is 2.5 times closer than Deimos to Mars. Thus, because we do not observe Deimos to be so affected, we must look elsewhere for the desired source of acceleration. Woolard (1944) says that mutual perturbations between the two satellites would not be adequate due to their very small size and relatively wide separation.

Atmospheric drag. Kerr and Whipple (1954) investigated the possibility that the interplanetary medium in the vicinity of Mars might be sufficiently dense to give the observed acceleration. A simplified version of their calculations, with modifications for recent findings, follows.

The drag force on a satellite moving through a resisting medium of density ρ is

$$W = \rho\, Qv^2$$

where Q is the cross-sectional area of the satellite ($Q = \pi r^2$), and v is its velocity relative to the medium. The increment of energy lost per revolution is

$$dE = -\,2\,\pi a W$$

where a is the semi-major axis. (dE should more properly be ΔE.) The relation between a and the orbital energy is

$$E = -\,GMm/2a$$

where G is the gravitational constant, M is the mass of Mars, and m the mass of the satellite (Phobos).

Differentiating E with respect to a gives

$$dE = (GMm/2a^2)\, da$$

From Kepler's Third Law, the orbital period is

$$u = GM\, a^{-3/2}$$

and the differential change in period per revolution is

$$du/u = -\ 3da/2a$$

Knowing that the velocity is given by

$$v^2 = GM/a$$

we arrive at

$$du/u = 9\pi a\rho/2r\rho_s$$

where ρ_s is the density of the satellite, assumed to be 3.5 gm/cm^3. Kerr and Whipple have converted Sharpless' acceleration into this form to be 8×10^{-12}. The other values used to derive the required density of the medium are:

$$a = 9300 \text{ km}$$

$$r = 12 \text{ km (larger than that used by Kerr and Whipple)}$$

The result is $\rho = 2.5 \times 10^{-15}$ gm/cm^3, which compares with Kerr and Whipple's 5×10^{-16} for an interplanetary medium which moves with respect to Mars. The interplanetary medium in the vicinity of Mars is estimated to be on the order of 10^{-20} gm/cm^3. But even if the resisting material were this dense, Deimos would also be affected, hence this explanation must be discarded.

Not considered at that time was the possibility that the Martian upper atmosphere might have the required density. Shklovskii (1959), after ruling out all causes for the acceleration except atmospheric drag, calculated the required density of Phobos assuming an exospheric density of less than 2×10^3 gm/cm^3 to get the observed acceleration. No natural substance with his resulting density of

10^{-3} gm/cm^3 can be imagined with enough cohesive force to remain so near Mars. Therefore Shklovskii concluded that Phobos might well be artificial, constructed as a large, hollow sphere by an advanced Martian civilization and launched hundreds of millions of years ago in their exploration into space. Herrera (1960) finds Shklovskii's proposal not unreasonable when one considers that our sun-orbiting satellites will remain long after our civilization is gone.

Schilling (1963) constructed a model of the Martian atmosphere extending up to 2600 km above the surface of Mars in which he shows that the density at that altitude may be as much as 7 x 10^{-16} gm/cm^3. Later Schilling (1964a) extended his model to 6000 km in the equatorial region where, due to centrifugal force and solar heating, the density might be as high as 10^{-16} gm/cm^3, nearly enough for the desired effect. He also suggested that gravitational concentrations of dust near Mars might increase his calculated densities, and concludes that the bizarre suggestion by Shklovskii (1959) that to get the observed acceleration Phobos must be a very low density sphere, is not required. Mueller (1966) sets a limiting altitude of 17,000 km, well below the height of Deimos, on that layer of the exosphere that could affect a satellite.

Schilling (1963) based his earliest model on a surface atmospheric pressure on Mars of from 40 to 100 mb. In his later study, Schilling (1964a) used an equatorial pressure range from 85 mb to 133 mb. Subsequently the Mariner IV probe (Anderson et al., 1965) has given 4 to 10 mb as more accurate values. Michaux (1967), in his up-to-date review of all the earlier methods, considers that "the additional observations made in 1965 from the radio-occultation experiment of Mariner IV's fly-by of Mars have now settled this long controversy." Although none of the earlier methods (photometry, polarimetry, and spectroscopy) produced results in this range -- the most likely value had been thought to be about 85 mb -- post-Mariner analysis has given considerable weight to the values of refractive index and scale height obtained by the Mariner experiment. As may be expected, analyses have also uncovered possible explanations for the earlier results being too high.

Schilling's results, already barely adequate to explain the acceleration, must now be entirely inadequate without the support of a high surface pressure.

Tidal friction. Although Schilling (1964a) seemed to have uncovered a plausible explanation for the acceleration, his article was answered by von Schelling (1964) and Redmond (1964). Von Schelling called attention to an apparent discrepancy in one of Sharpless' parabolic terms, but Redmond moves to the very real possibility that tidal forces may be as effective as atmospheric. In an earlier paper, Redmond and Fish (1964) show what assumptions about Mars' surface must be satisfied if tidal friction is to be a significant factor. A tidal lag of only $1^\circ.1$ to $1^\circ.4$ would be adequate if the mantle of Mars is assumed to be less rigid than the model of Bullen (1949), which holds that the primitive composition of the Martian crust is much the same as Earth's crust.

Öpik (1962) gives the rationale for this phenomenon. Since Phobos moves faster than the surface of Mars, the tidal bulge on the surface of Mars would lag behind, tending to retard Phobos, reducing its angular momentum and causing it to spiral inward. It is the lag angle of this tidal bulge and its size that are the critical parameters in determining the importance of tidal effects. Opik gives the rate of change of the period u of a satellite as

$$\frac{1}{u}\frac{du}{dt} = \frac{CKmR^5}{M^{1/2}\ a^{6.5}} = \frac{9km}{M}\left(\frac{GM}{a}\right)^{1/2} \frac{R^5 \ \sin\theta \ \cos\theta}{a^6}$$

where

C = universal constant

K = relative coefficient of friction of Mars (K = 1 for Earth-Moon system)

k = relative height of the bulge above its equilibrium height

R = radius of Mars

θ = lag angle of the tidal bulge

Recent studies of the Earth have shown that tidal distortions in the Earth's mantle contribute a major part of the tidal friction associated with the Earth-Moon system. It is not necessary to postulate ocean surfaces on Mars to arrive at a substantial effect.

A preliminary estimate by Kerr and Whipple (1954) based on the methods of Jeffries and assuming the mantle of Mars to be of the same rigidity as that of the Earth resulted in a tide 800 times too small for the observed effect. Jeffries (1957b) in a later analysis concluded that only one part in 10^4 of the supposed acceleration of Phobos could be due to tidal friction. But all of these calculations are very sensitive to assumptions regarding the structure of Mars which is not well understood. Results of the Mariner IV experiments indicated the absence of any measurable magnetic field near the planet. It is likely then that the internal core of Mars is not molten and that there may be other basic structural differences from the Earth. Even the optimistic view of Öpik (1962), which considers the coefficient of friction K (depends on the structure and rigidity) of Mars to be the same as that of the Earth, accounts for only one-tenth of the observed acceleration. Mueller (1966) suggests the possibility of a bulge on the back-side of Phobos which would contribute to tidal friction energy losses.

Wilkins (1965, 1966) in his analysis of all the suitable observations from 1877 to 1928 to improve the orbital elements of both satellites used an assumption built into his computer program that there was no secular acceleration in longitude, only a perturbation in the orbits due to the oblateness of Mars. His results showed conclusively that with a rejection limit of only 2 seconds of arc, the data fit such a model. Choosing a small value for longitudinal acceleration did nothing to improve the fit of the data. Moreover, the new orbital elements (given in part in Table II) were found to give a satisfactory fit to the 1941 and 1956 observations without the postulation of a secular acceleration in the motion of Phobos. These more recent observations, given as relative positions of the two satellites, were not directly adaptable to Wilkins' computer analysis for obtaining revised orbital elements. The new elements were also used to obtain revised estimates of the mass and oblateness of Mars which do not differ substantially from earlier values similarly derived. It remains only to test the 1967 observations, principally those carried out in this country by Pascu (1967) and Roemer (1967), against these revised orbital elements.

One then must ask what fundamental differences in approach caused Sharpless to find an acceleration and Wilkins not. Previous to Wilkins' analysis elliptic elements had been derived based on the observations of each observer separately for each opposition, and the secular perturbations in the orbit (due primarily to the oblateness of Mars) were neglected. Sharpless used the data collected by Burton (1929) and summarized by him into only 28 values of longitude for the period from 1877 to 1926. Sharpless also accepted Burton's error estimates, which by Wilkins' study are shown to be too low. Wilkins, however, used all available observations of each satellite to determine a single least-squares solution of all the elements with perturbations both from oblateness and from the Sun included. He studied some 2700 observations checking for the amount of scatter in results for each observer, finding the longitude estimate that best fit and weighting the groups of data according to the amount of error that was apparent. The 1941 data gave a residual in longitude opposite in direction to that predicted by Sharpless, and the 1956 data yielded a residual much smaller than Figure II would extrapolate to.

CHAPTER IV

OBSERVATIONS WITH THE UNIVERSITY'S 20-INCH REFLECTOR

The opposition of Mars on April 15, 1967, was not considered a favorable one. At closest approach six days after opposition Mars was at 0.601 a.u. compared with 0.378 a.u. at the favorable opposition of 1956. By comparison the 1963 opposition, at 0.670 a.u., was the poorest in the present fifteen year cycle between perihelic oppositions. Nevertheless, this observer considered that under favorable atmospheric conditions it might be possible to photograph the Martian satellites using the 20-inch reflector located near the University of Maryland campus. Personal communications with experienced observers in the Washington area were not encouraging, but it was determined that even unsuccessful attempts would be instructive, providing a feel for the problems that are involved in photographing a faint object in close proximity to a very bright one. Mars was brighter than Phobos by 13 magnitudes. A more meaningful measure, since Mars is not a point source, is the factor of 10^5 difference in brightness. If successful, the results might be used to check the position of Phobos against the predicted position to provide evidence for or against any secular acceleration.

A Japanese observer, Takeshi Sato (1967), in refuting a categorical statement by Shawcross (1966) that a 12- to 15-inch telescope is required, claims that during the favorable 1956 opposition Deïmos was observed with a 6-inch telescope on one occasion and that Phobos was observed with an 8-inch telescope. Photography of this type of object is considered more difficult than visual detection.

There follows a discussion of each problem area that needed to be overcome, and the steps that were taken to increase the chances of obtaining useful photographs.

Photographic materials and techniques. Although two-year old IIaE photographic plates were available for the initial experimenting and familiarization with the equipment, it was necessary to determine the best type of plates to be used for serious observations near opposition. Plate size, 4 by 5 inches, was dictated by the type of plate holders available. This corresponds to an area of sky of about 44 by 55 minutes of arc, and the telescope field of view is a circular area of about 30 minutes of arc diameter. Backed plates were ordered to reduce halation, a serious problem due to the brightness of Mars and the long exposure times required. Type IIaD spectroscopic plates were selected for their adaptability to exposure times longer than 2 to 5 minutes, medium contrast, resolving power, and granularity. This type has the flattest characteristic curve (lowest contrast) of all the commercially available spectroscopic plates. Spectral sensitivity class D is particularly sensitive in the region from 4600 Å to 6300 Å which in effect limits the sensitivity in the red where the planet tends to be the brightest. Type IIa plates are the only ones for which the slow developer, D-76, is recommended by Kodak (Publ. P-9, 1967) as an alternative to the more common D-19 developer. Adjacency effects as described by Stock and Williams (1962) are reduced not only by agitation but also by the use of a slow developer. D-76 was used for all but one of the Mars plates, but to save time D-19 was used for focus plates and preliminary work.

Although filters were not available for mounting on the telescope until the week before opposition, standard U, B, and V filters were employed to minimize glare from Mars and sky brightness. Johnson (1963) defines these filters as having bandwidths of about 1000 Å centered on 3500 Å (U), 4300 Å (B), and 5500 Å (V). Considering the importance of gathering as much light as possible from the satellites, clearly the U filter does not match the spectral sensitivity region on the emulsion being used, and would not be satisfactory. The B filter was the best suited to these observations in that it limited the brightness of Mars without significantly diminishing the amount of light from the satellites. (See page 11.) However, the B filter was not effective in reducing night sky radiation, particularly a problem near opposition when the Moon was nearly full. The V filter, being centered in the sensitivity region of the emulsion would pass the most light and would be somewhat effective in reducing sky background, but it would do little to reduce the glare of the planet.

This glare may be attributed to three causes:

(1) Atmospheric scattering. Haze is an extreme case.

(2) Scattering of light within the optics of the telescope. Dust on the mirrors would be a significant contributor.

(3) The turbidity of the emulsion. Mees and James (1966) write that scattering is a factor with small grain size, whereas in emulsions of coarse granularity, reflection and refraction at the grain surfaces would tend to be important.

The University of Maryland's 20-inch folded Cassegrain telescope, primarily a teaching tool, has several significant limitations. The clock drive is very accurate; no drift attributable to the drive was noticed even for exposures as long as 12 minutes. But no variable speed drive is available, and proper tracking is dependent on carefully balancing the telescope about all three axes. Balance often became a problem especially at times when observing time was of necessity shared with other projects mounting other equipment on the telescope. Proper balance was very difficult at hour angles greater than about $\pm 2^h$. Mars, at -7° declination, was not visible above the trees at less than $- 2^h 45^m$ hour angle (east) or more than $+ 3^h 15^m$ (west).

Focus is a sensitive function of temperature, and it is of critical importance in photographing faint point sources. Focusing was accomplished by manually sliding the brass plate holder tube in (or out) to several positions in steps of 1/4-inch to find the position giving the smallest image of a selected star. An error of 1/4-inch gave an unacceptably out-of-focus image. On observing nights the temperature ranged from 3°C in early March to 18°C late in May. Focusing position varied irregularly over a range of nearly an inch depending upon temperature.

No special alterations to the telescope were made to reduce the problem of diffraction over the long exposure times. Kuiper in 1956 using an 82-inch telescope used an eccentric diaphragm to eliminate diffraction spikes, and Pascu (1966) suggests the use of black velvet sleeves on the secondary supports to help reduce diffraction spikes when it is not feasible to reduce the aperture with a diaphragm. Figure III shows how the bright diffraction ring occurred at a radius of approximately 1500 microns (on the plate) from the center of the image of Mars. The ring was not in a position where it would obscure Phobos or Deimos near their maximum elongations. The diffraction spikes, also visible in Figure III, were not a serious problem in that the observations could be made when the satellites were well clear of the spikes.

Pascu (1967) observed the satellites during April 1967 using the U.S. Naval Observatory 61-inch reflector at Flagstaff, Arizona. With a specially constructed plate holder, he was able to position a filter with a semi-opaque spot over the image of Mars so that the limbs of the planet would be distinct yet the satellites would be visible beyond the limits of the spot. Such an arrangement allows astrometric reduction of the plates by providing accurate positions of the satellites with respect to the center of the apparent disk. At this writing his plates had not yet been measured.

For this writer's observations, an opaque masking device was designed and constructed not to reduce diffraction, which occurs in the optics before the light is focused at the photographic plate, but to stop the direct light from Mars from reaching the emulsion. That intense light would otherwise be scattered within the emulsion, fogging it well beyond the image of the disk. It was necessary somehow to position the mask over the bright disk of Mars without obstructing the light from the satellites. With the available plate holders it was impossible to position a small filter, or mask, accurately over the image of the planet. But it was possible to position the image of Mars near the center of the plate using the finding telescope and hold it in that position while the

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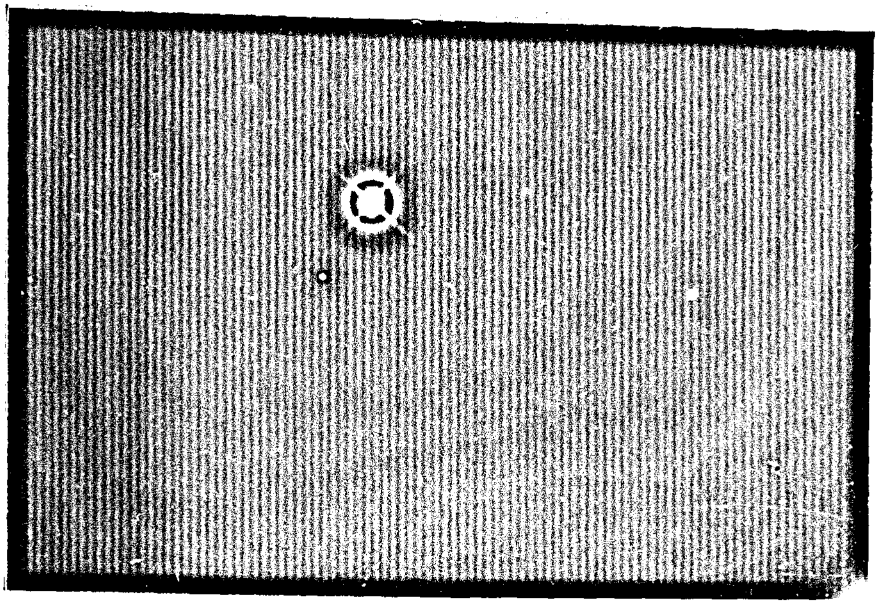

Figure III. Mars with its associated diffraction pattern. Photographed on the 20-inch folded Cassegrain at College Park, Maryland, 0858 U.T., March 10, 1967. f/15, 90 second exposure, IIaE emulsion, no filter. Scale: 1 mm = 13".5. The star SSE of Mars is 96 Virginis at m = 6.5.

plate might be moved along a straight line for several exposures. Figure IV shows the slotted mask, enlarged to twice its actual size. It was made from a 4- by 5-inch spectroscopic plate with the emulsion and backing removed. The opaque material was commercially available, Zip-a-Line brand poster tape, 1/16-inch wide. Lengths of this tape were stretched into a straight line and attached to the glass at the proper angle and at spacings such that as the plate holder was moved to give six images of the planet spaced 1/2-inch apart, one of the images would be entirely covered yet the satellite of interest would be visible. Although this masking device would in principle have been effective, observing conditions as described below did not improve sufficiently to permit it to be

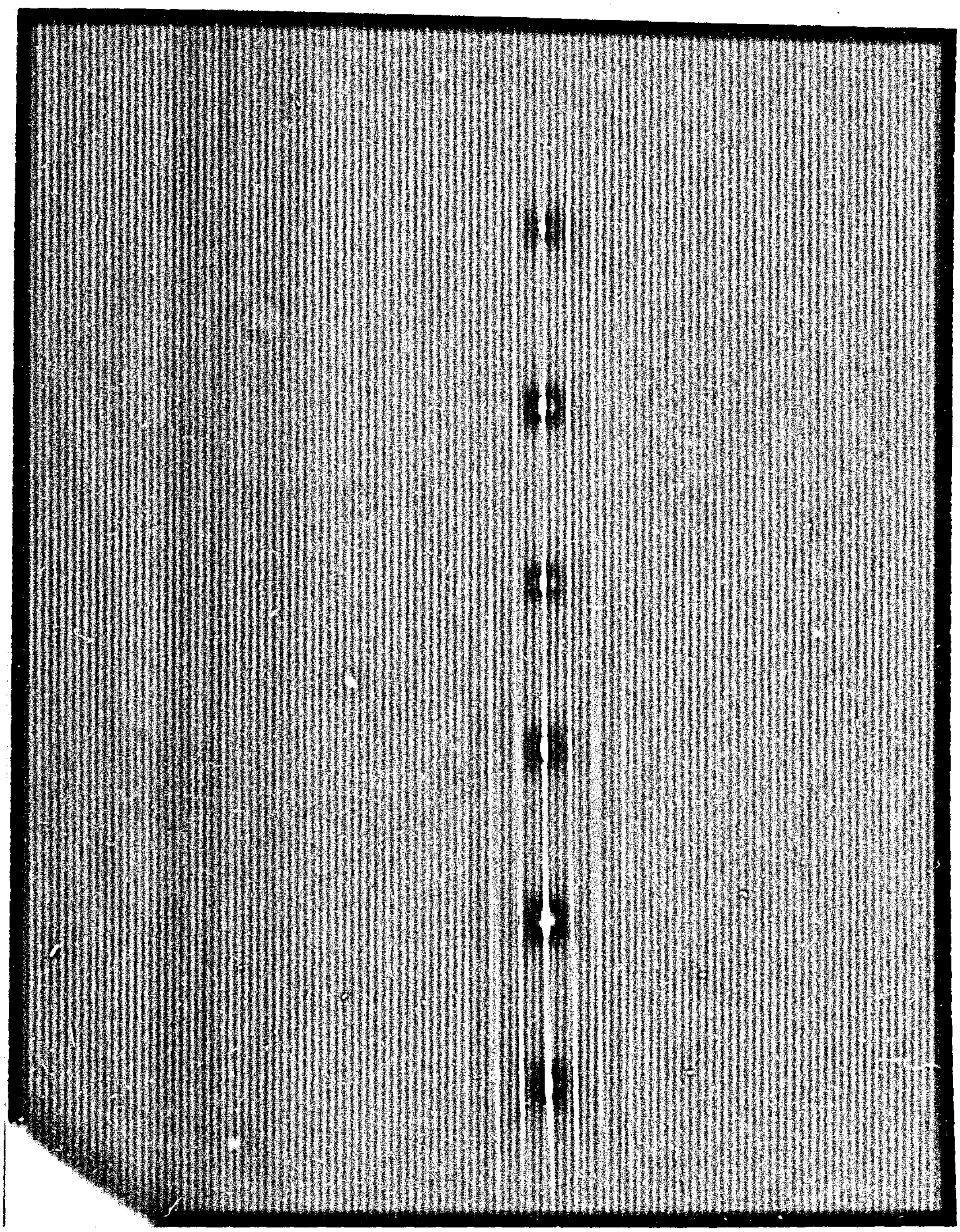

Figure IV. Slotted mask with six exposures of Mars.
30 second exposures, 0615 - 0635 U.T., April 9, 1967. All other data are the same as for Figure III.

given a fair test.

Weather and observing conditions. On each assigned observing night during the period from mid-March through May, there was a six hour period when Mars was visible above obstructing trees. During this six hour period Phobos could be expected to be near either east or west maximum elongation at least once, more often twice. Deimos was near enough to one of its maximum elongations for approximately six hours of its thirty hour period; therefore, it would be observable during slightly more than half of the available observing periods. But atmospheric conditions had to be perfect at these special times when observing was dictated. Table III, a chronology of observations, gives some indication of weather problems on nights when at least an attempt appeared to be warranted. Overcast nights are not included, nor are nights when observations were aborted due to weather before Mars plates could be made.

On even the best of the Mars plates obtained, poor seeing conditions, up to 5 seconds of arc, smeared the images of faint field stars (approximately 12^m) enough to make the satellites not detectable in the glare of the planet. The magnitudes of the field stars were estimated by identification on the Palomar Sky Atlas and comparison with Bonner Durchmusterung (B.D.) charts.

Table III

Chronology of observations

Date		Weather/conditions	General results
March	9	Clear	Mars at various exposure times. Sky brightness noticeable at 6^m.
	26	High thin scattered cirrus, haze, near full Moon	Short exposure times on Mars for studying diffraction and effect of full Moon. Some sky brightness at 4^s exposure.
April	8	High thin cirrus	Experiment with slotted masking device at 30^s exposures. No sky brightness effect.
	15	Considerable haze	[All the following entries are long exposures of Mars.] B filter available and used. Excessive sky brightness.
	17	Widely scattered cirrus, changing to low clouds and haze	Clouds forced termination of schedule. Plates badly fogged by haze.
	20	Clear, becoming hazy before Mars exposures, near full Moon	Haze not measurably helped by V or B filters.
	22	Clear, full Moon	Plate badly blackened by sky brightness, strong reflection of Moon, badly out of focus due to operator error.
	30	Clear	Good plates, poor focus
May	8	Widely scattered cirrus near end of period	One good plate, another plate degraded by poor tracking at high hour angle.
	28	Clear	Good plates, slightly darkened by evening twilight.

CHAPTER V

SUMMARY AND CONCLUSIONS

It is not uncommon for authors to dilute their conclusions with the statement, "Further data/observations are necessary." With regard to Phobos and Deimos, there are clearly enough unanswered questions and tentative conclusions to warrant such a statement.

Sharpless (1945) said, "If an acceleration exists, more observations will be required to confirm it."

Shklovskii and Sagan (1966): "Only when new and very precise observations are carried out will we be able either to disprove or verify Sharpless' results."

Wilkins (1965): "Further progress will depend largely on new observations being made." And (1966): "We hope also that astronomers having access to large telescopes will take the opportunities at the next opposition in April 1967 to obtain new measures of the positions of the satellites and of the size and shape of Mars."

Aside from the recognized need for analysis and refinement of ephemerides, probably the highest priority should be given to color and size measurements. The photoelectric area scanner described by Rakos (1965) could be used to advantage here.

The above comments notwithstanding, some definitive conclusions can be drawn from the available data.

The mystery behind Swift's predictions are largely removed when one considers what reasonable number of moons he would pick: two, an interpolation between the supposed number of moons of the other nearby planets. Their distances were picked as proportionately the same as Jupiter's two inner moons (as known in his day), and their periods were calculated to fit Kepler's Law.

The sizes of the two satellites are still not known within a factor of about two due to the lack of color and albedo data.

Wilkins' (1965) recent analysis of all the usable observations to date casts serious doubt as to the reality of secular acceleration in the longitude of Phobos. This author concludes that no secular acceleration exists, based on Wilkins' analysis which was far more complete than that of Sharpless (1945) and included a longer time span. The alternative, that there is in fact a measurable acceleration, is not supported by adequate explanation. Of all the proposed causes of a secular acceleration, tidal friction would seem the most plausible but only because the magnitude of that effect is based on assumptions about the nature of the mantle and interior of Mars that are supported by insufficient data.

This author's experience in attempting to photograph the satellites supports the rule-of-thumb that unless the objects are visually detectable with a given telescope system, they are not likely to be photographed with that telescope under those conditions. Further experimentation with the slotted mask design might be done on Jupiter V which poses detection difficulties comparable to Mars' satellites. An easy refinement might be to obtain a mask of similar design of any desired density by exposing a high-resolution spectrographic plate through a plate with the opaque strips positioned to give the clear slots.

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